ECEMP 2025

Coping with the Dunkelflaute

Power sector implications of variable renewable energy droughts in Europe

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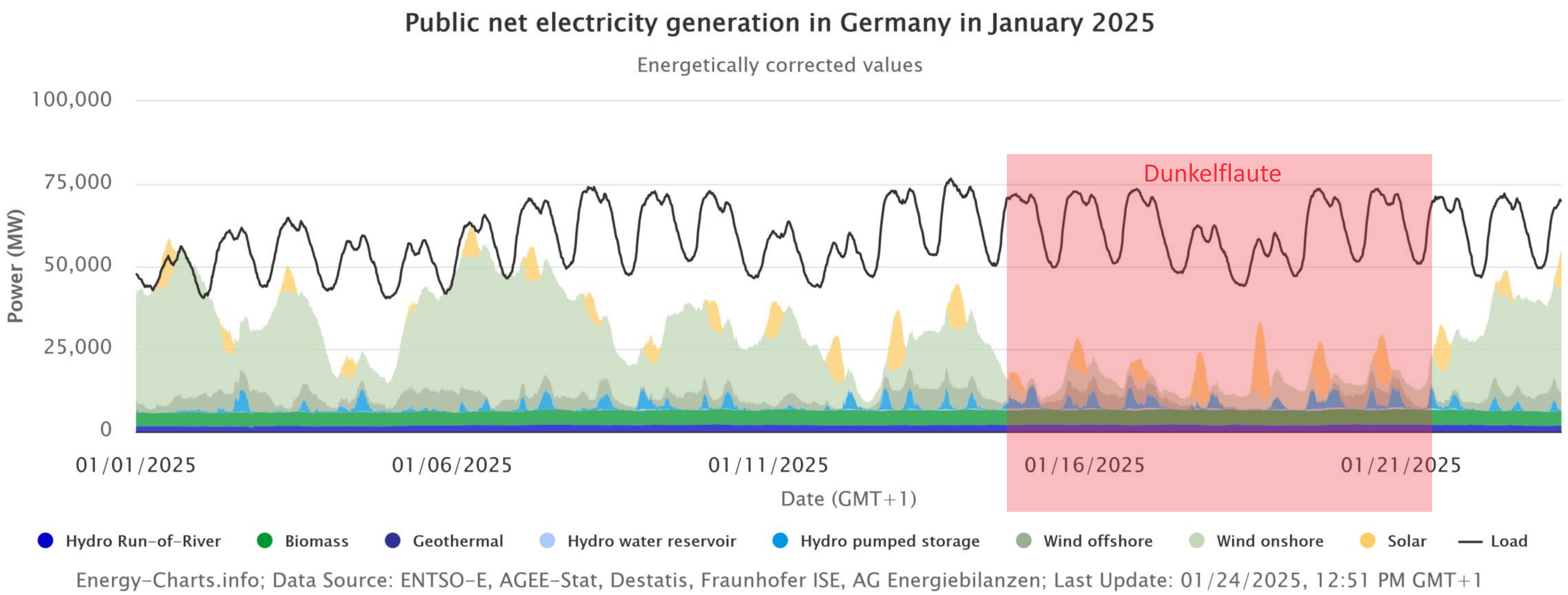
Berlin, 16 October 2025

Content

1. Motivation

Recent Dunkelflaute event in Germany

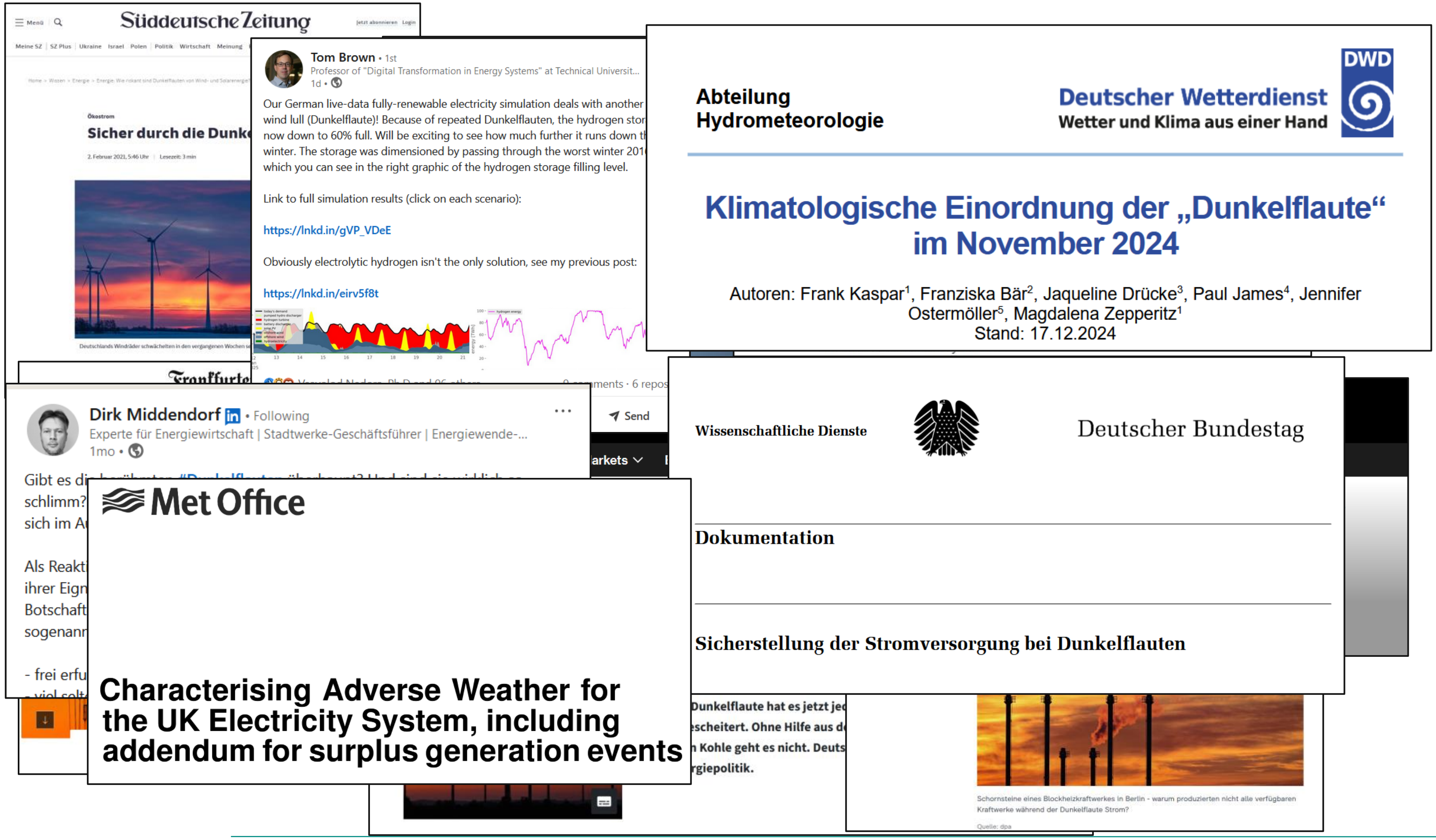


Variable renewable energy (VRE) drought or German term "Dunkelflaute"

- Extended period with low renewable availability
- Increasing reliance on VRE → Dunkelflaute events become key challenge for realizing energy transition
- Temporal and spatial flexibility for dealing with these periods

Relevance

Dunkelflaute events in public, policy, and academic discourse



Research Questions

European power sector implications of extreme Dunkelflaute events

VREDA

1. What are most extreme Dunkelflaute events? — Kittel & Schill (2024a), Kittel & Schill (2024b)

DIETER

2. What is their impact on long-duration storage operation and investment?
3. What is the value of alternative flexibility in terms of…
   - Cross-country electricity and hydrogen exchange?
   - Interaction of various flexibility options?
   - Firm zero-emission capacity?
   - Fossil-based backup capacity with CSS?
4. Are there critical historical weather years?

Kittel, Roth, and Schill (2024)

2. Research design

Research design

100% renewable European power sector

- No fossil fuels, CCS, or nuclear power (relaxed in sensitivity)
- Import of green hydrogen possible
- Largely parameterized to TYNDP 2022 - Distributed Energy
- Sector-coupling “light”: simplified industry, heat, transport

Scenarios: temporal dimension

- 35 independent runs based on 35 historical weather years (1982 – 2016)
- Source: Pan-European Climate Database 2021.3
- summer2summer planning horizon

Scenarios: spatial dimension

- Different interconnection levels

Interconnection

Island → **European copperplate (CP)**

(1)
Electricity: no
Hydrogen: no

(2)
Electricity: TYNDP
Hydrogen: no

(3)
Electricity: TYNDP
Hydrogen: TYNDP

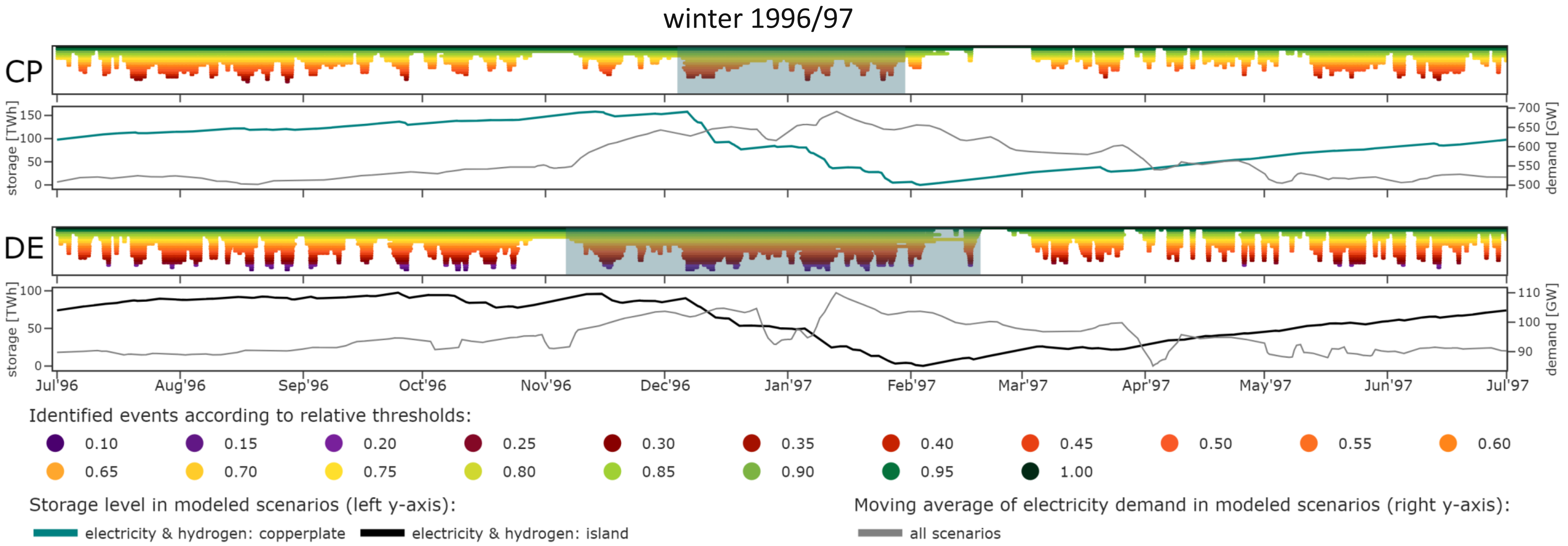
(4)
Electricity: copperplate
Hydrogen: copperplate

3. Key insights

Identification of extreme Dunkelflaute events

Identification based on wind and solar availability time series (VREDA)

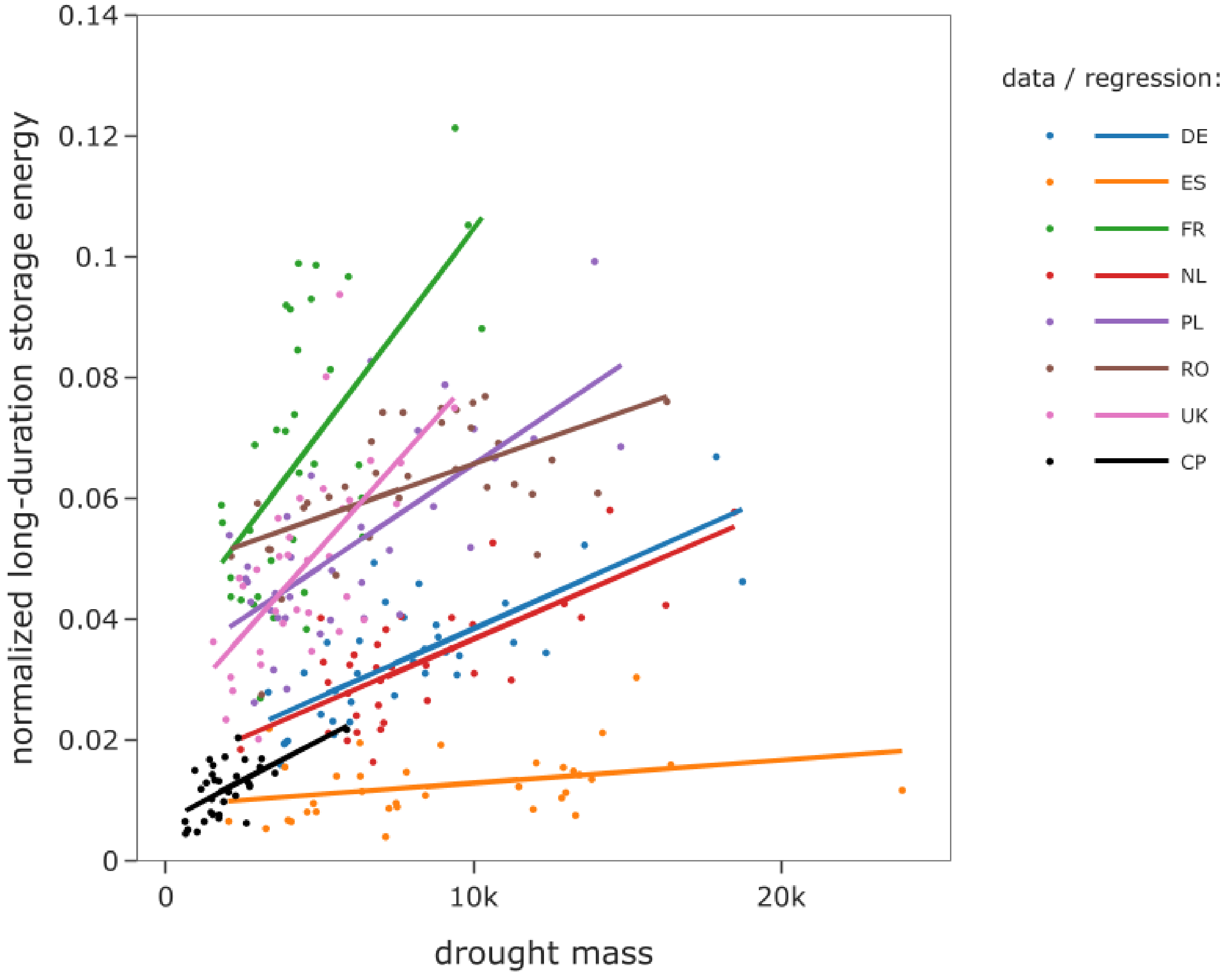
- No meaningful definition for extreme Dunkelflaute events
- Drought mass metric to find events that drive long-duration storage discharge
- Sequence of severe shortage events within a long-lasting, contiguous low-availability period
- Span across turn of year
- Most extreme European event in the data in winter 1996/97



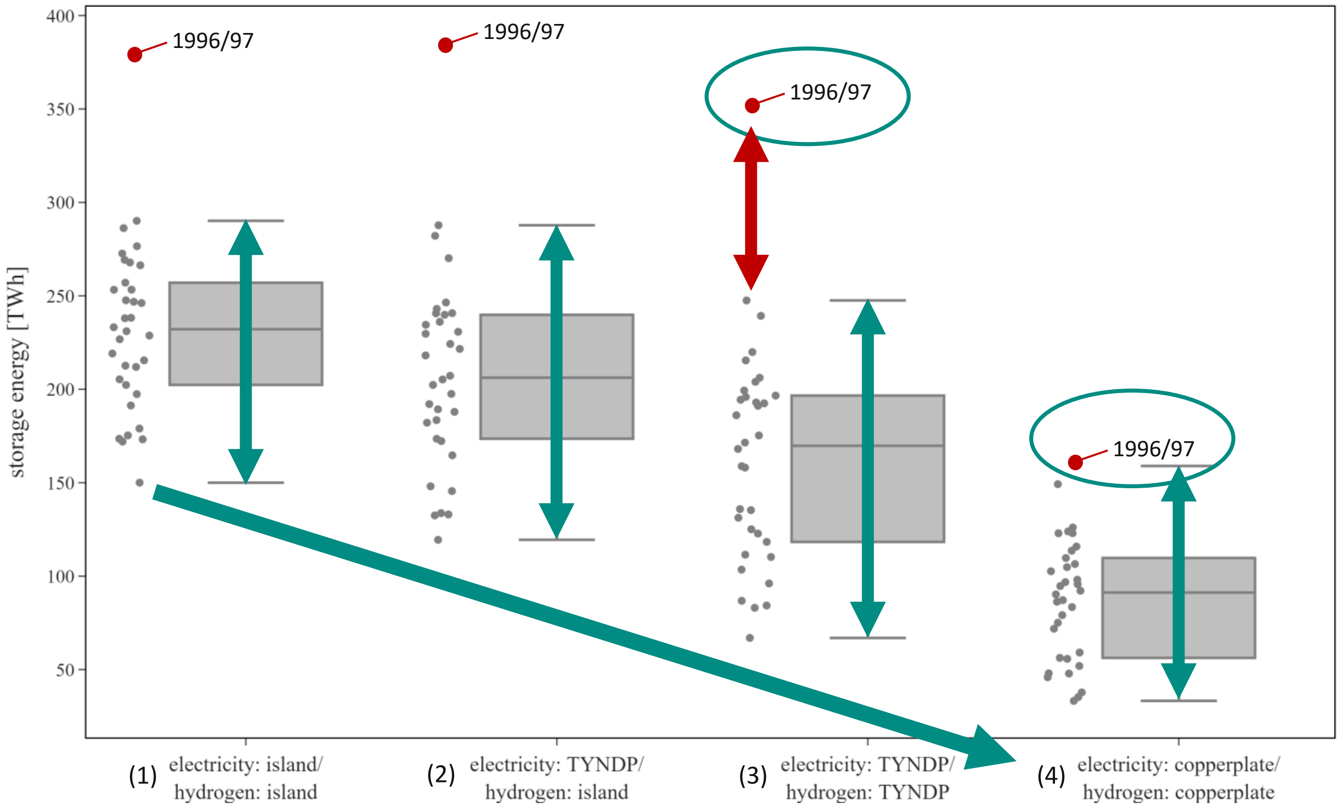
Long-duration electricity storage investment

- Most extreme Dunkelflaute events drive long-duration storage energy capacity

- Further drivers
  - Other flexibility options
  - Demand seasonality



Long-duration electricity storage (LDS) needs



- Geographical balancing decreases LDS need, but significant levels remain
- Inter-annual variation across weather years → input data matters
- 1996/97 highest LDS need due to European scale of Dunkelflaute → weather-resilient energy system modeling
- Copperplate scenario (4): 159 TWh → minimum need, "no regret" investment
- TYNDP scenario (3): 351 TWh → policy-relevant investment, exceeding next highest storage need in 1984/85 by 42%

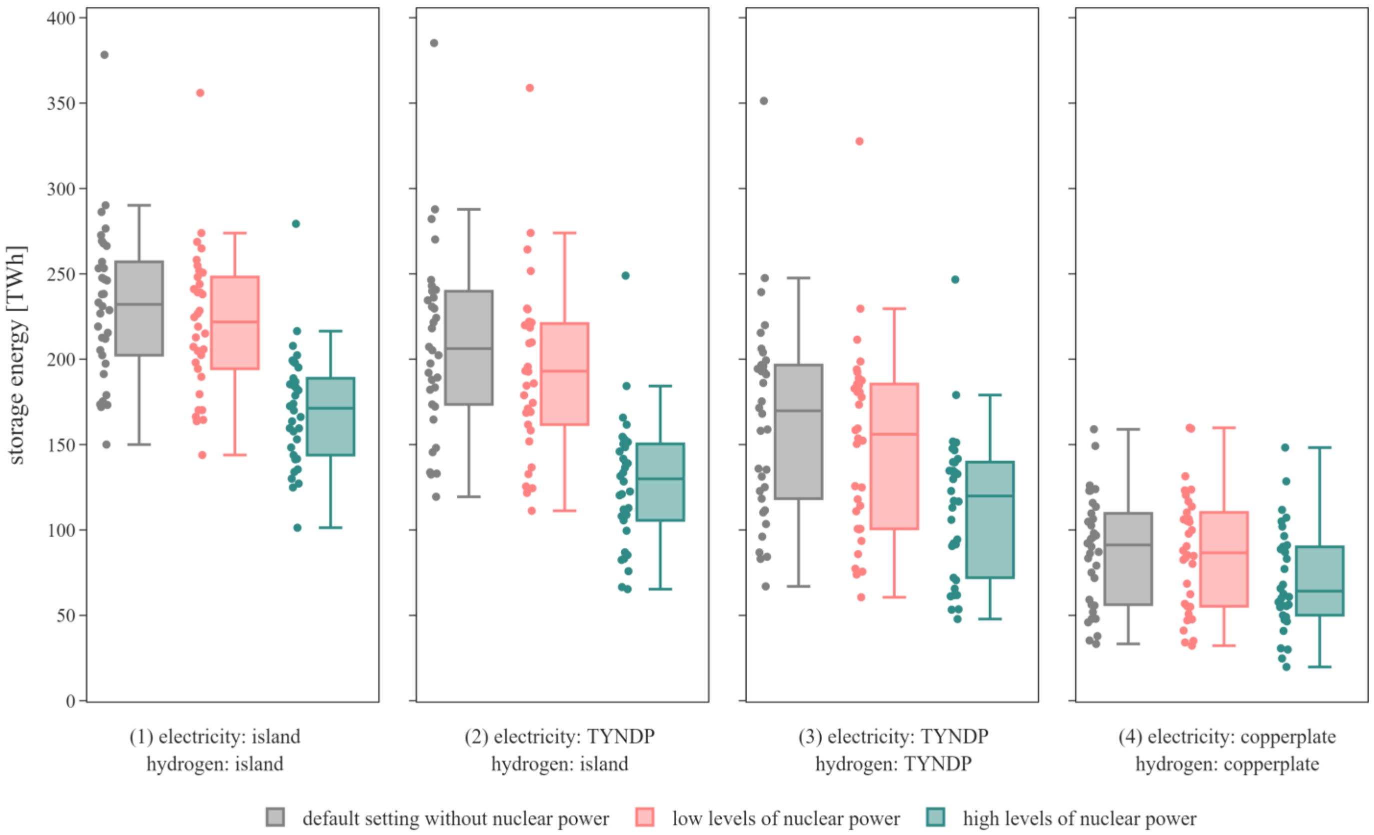
Sensitivity analysis: Impact of nuclear power

Exogenous nuclear capacity

- Low (24 GW) and high (102 GW) levels of nuclear power acc. to TYNDP 2022

General effects

- Nuclear provides firm generation during extreme Dunkelflaute events
- Nuclear displaces optimal investment in wind and solar, decreasing the system's flexibility need
- Mitigation of storage needs under policy-relevant interconnection (3)
  - Low: 8/7% mean/max reduction
  - High: 29/30% mean/max reduction



5. Conclusion

Conclusion

Policy implications

- Dunkelflaute events drive long-duration storage operation and investment
- Extreme years with substantially higher storage needs
- Interconnection can mitigate storage needs to a limited extent
- Nuclear power can mitigate storage needs
- Fossil backup capacity incl. DACCS or load shedding unlikely to mitigate storage needs

- Long-duration storage indispensable for renewable energy system
  - Long lead times (5-15 years) → early adoption for rapid scaling including deployment incentives required

Conclusion

Modeling implications

- Choice of weather year matters → 1996/97 relevant (not in TYNDP 2022)
- Model planning horizon maintaining complete winter periods
- Computational restrictions → Dunkelflaute identification based on renewable availability time series supports the selection of critical weather years

Literature, code, and data

- Kittel & Schill (2024a): “Measuring the Dunkelflaute: How (not) to analyze variable renewable energy shortage.” Environmental Research: Energy 1.3 (2024): 035007.

- Kittel & Schill (2024b): “Quantifying the Dunkelflaute: An analysis of variable renewable energy droughts in Europe.” arXiv preprint arXiv:2410.00244.

- Kittel, Roth, and Schill (2024): “Coping with the Dunkelflaute: Power system implications of variable renewable energy droughts in Europe.” arXiv preprint arXiv:2411.17683.

Thank you for your attention.

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Backup

Power sector modeling

DIETER – Dispatch and Investment Evaluation Tool with Endogenous Renewables

- Open-source power sector model
- Linear partial equilibrium model → minimizes total system costs
- European setting with simplified grid representation (one node per country)

Input

Techno-economic parameters
- Renewable generators
- Storage
- Hydrogen + reconversion

Hourly time series on country level
- Renewable availability
- Electricity & hydrogen demand

Transfer capacity
- Electricity
- Hydrogen

Model

Total system cost → MIN
- Annualized investment costs
- Fixed & variable costs

Subject to
- Electricity provision at all times
- Generation restrictions
- System flexibility through storage and interconnection

Output

Investment decisions (capacity)
- Conventional generators
- Renewable generators
- Storage
- Electrolysis

Hourly dispatch (energy)
- Conventional generation
- Renewable generation
- Storage operation
- Electrolysis operation

Characterization of Dunkelflaute events

Renewable droughts patterns in 1996/97

Solar PV

- solar seasonality drives droughts

On- and offshore wind

- droughts primarily in summer, some also in winter

VRE portfolio

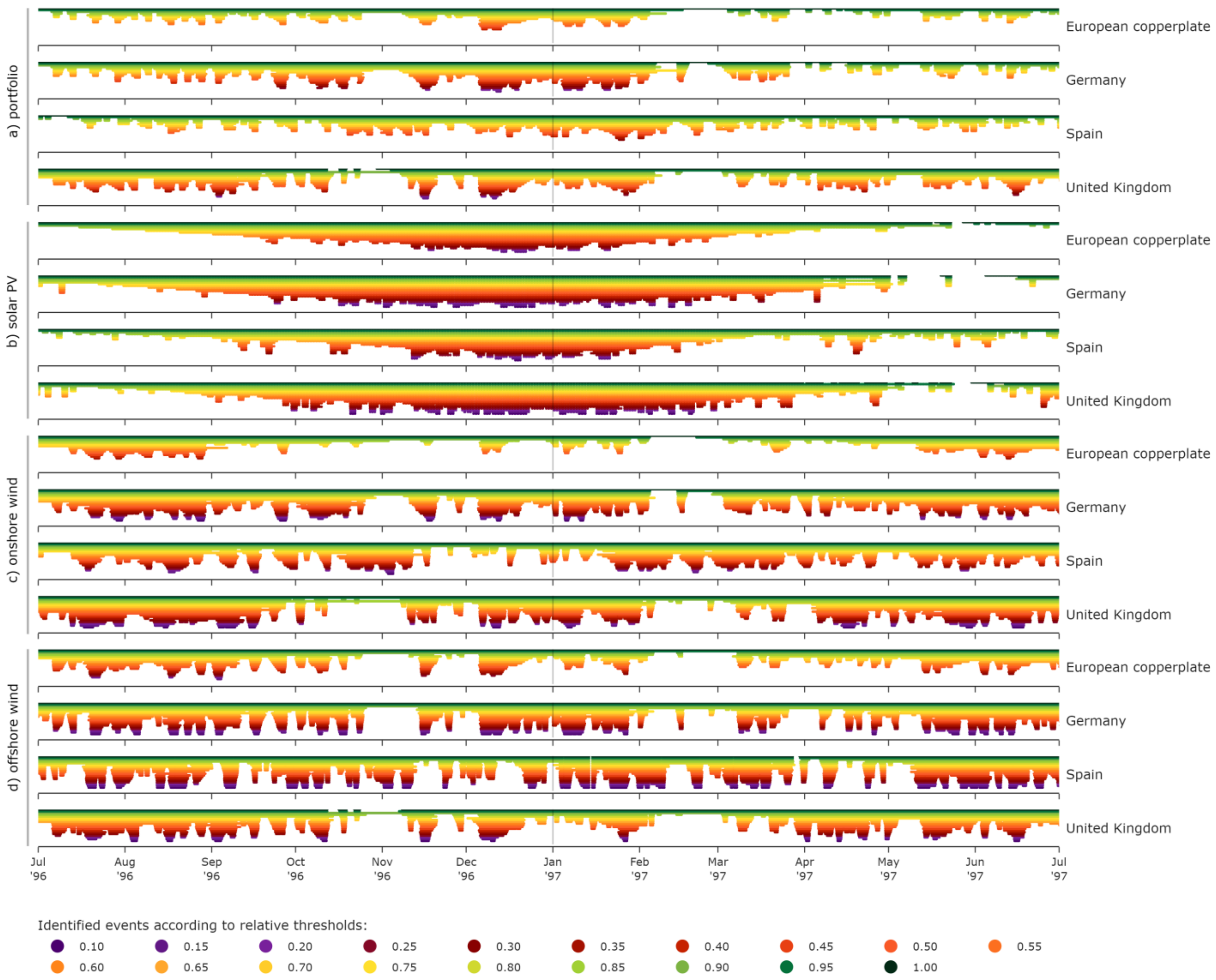
- product of solar seasonality and significant wind droughts

Portfolio effect

- complementary wind and solar availability profiles reduce drought severity of VRE portfolio

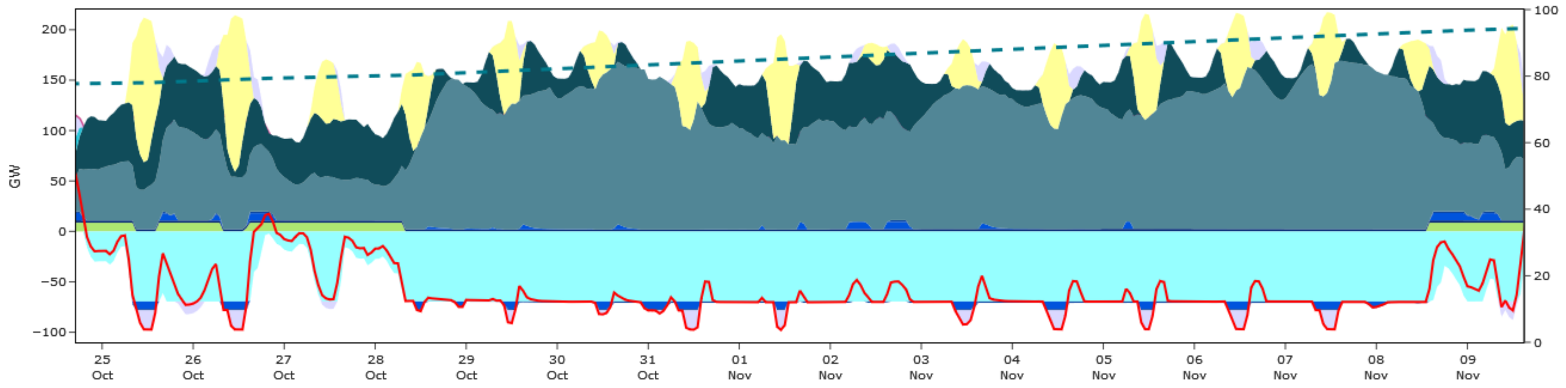
Balancing effect

- spatial smoothing of single technologies/VRE portfolio droughts



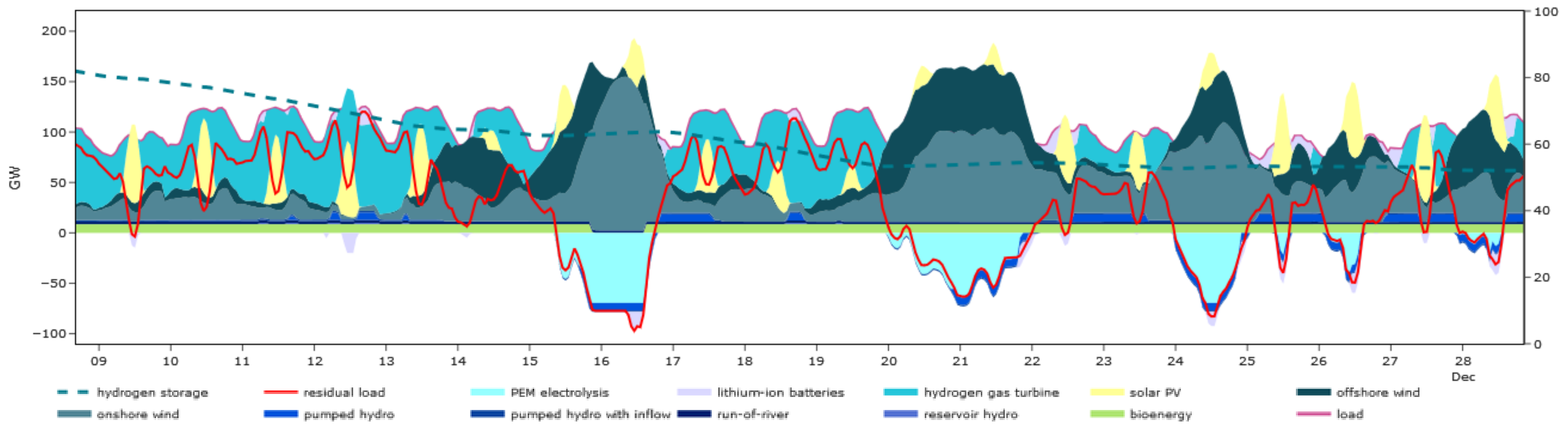
Interaction of flexibility options

Power sector operation in Germany before extreme droughts



- Battery cycling, hydro and biomass generation to enable more consistent electrolysis operation (even in positive residual load periods)
- Effect: reduce costly electrolysis capacity

Power sector operation in Germany inside extreme droughts



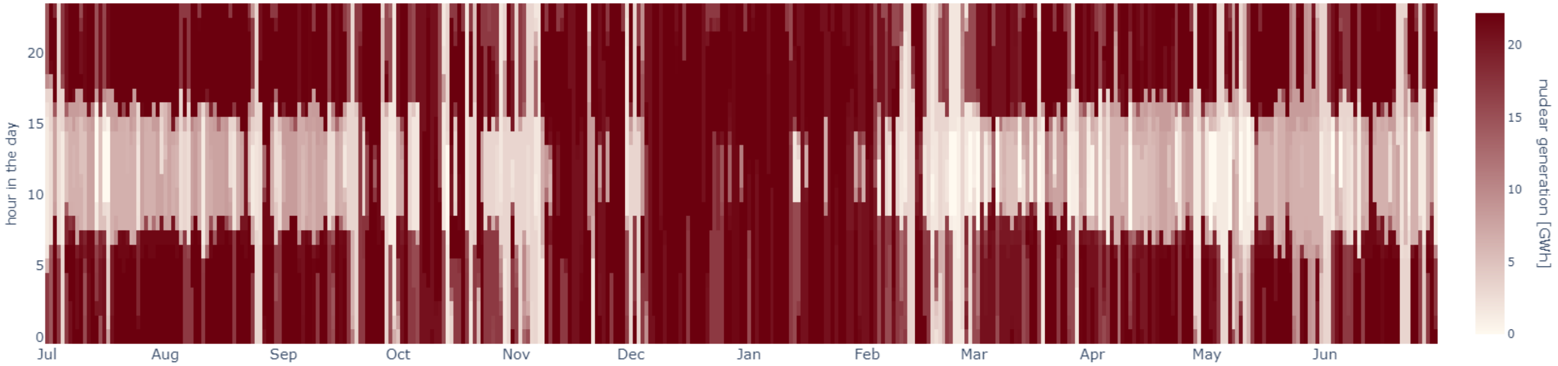
- Battery cycling powered by long-duration storage discharge
- Effect: reduce hydrogen turbine capacity entry
- Storage merit order for brief periods of positive residual load
- Effect: higher efficiency

Sensitivity analysis: Impact of nuclear power

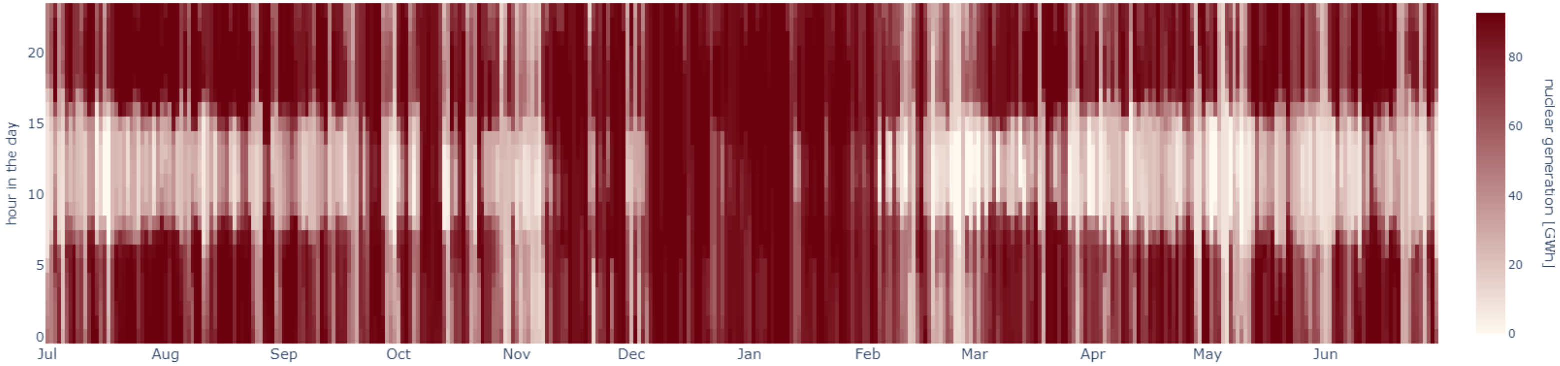
Operational patterns of nuclear power in winter 1996/97 under policy-relevant interconnection (3)

- Flexible operation to complement diurnal solar PV fluctuations
- Continuous dispatch during extreme Dunkelflaute events → reduces optimal long-duration storage discharging and energy capacity

Low levels of nuclear



High levels of nuclear



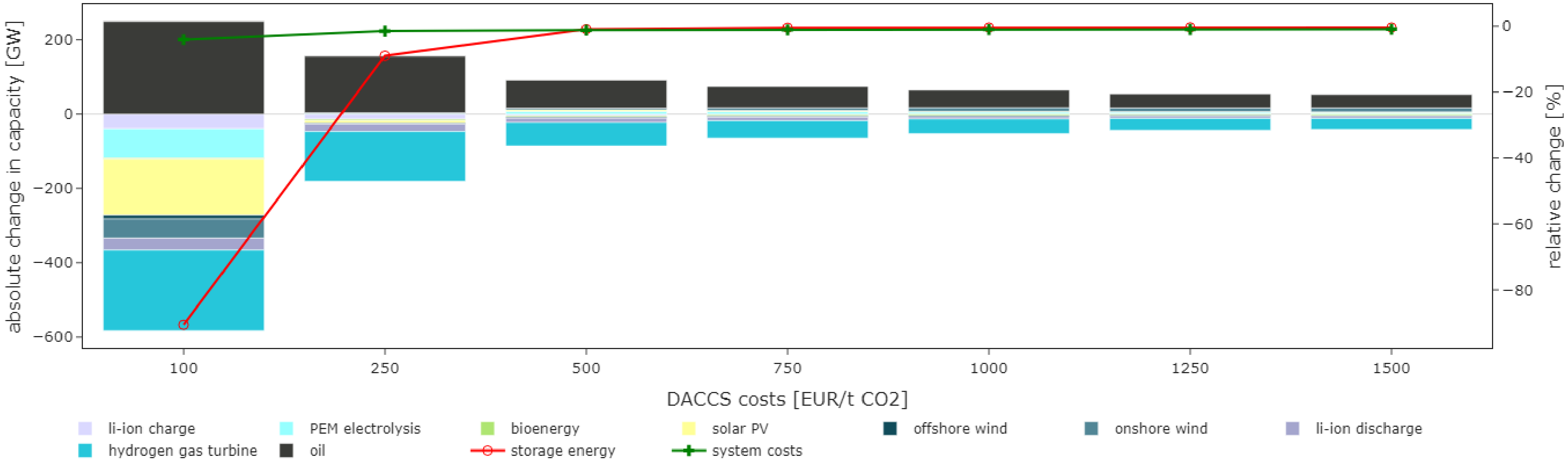
Sensitivity analysis: oil-fired backup capacity with CCS

Endogenous backup capacity

- Oil can be storage above ground and transported via trucks → no capital-intensive infrastructure requirements
- DACCS costs very uncertain → depends on policy support, economies of scale, technological learning curves, and the profile of its electricity demand

Impact in winter 1996/97 under policy-relevant interconnection (3)

- 100€/t CO2: substantial substitution effects and 4% systems costs reduction → long-duration storage remains optimal
- Higher DACCS costs: substitution of storage discharging capacity and 1% system costs reduction → long-duration storage energy hardly affected



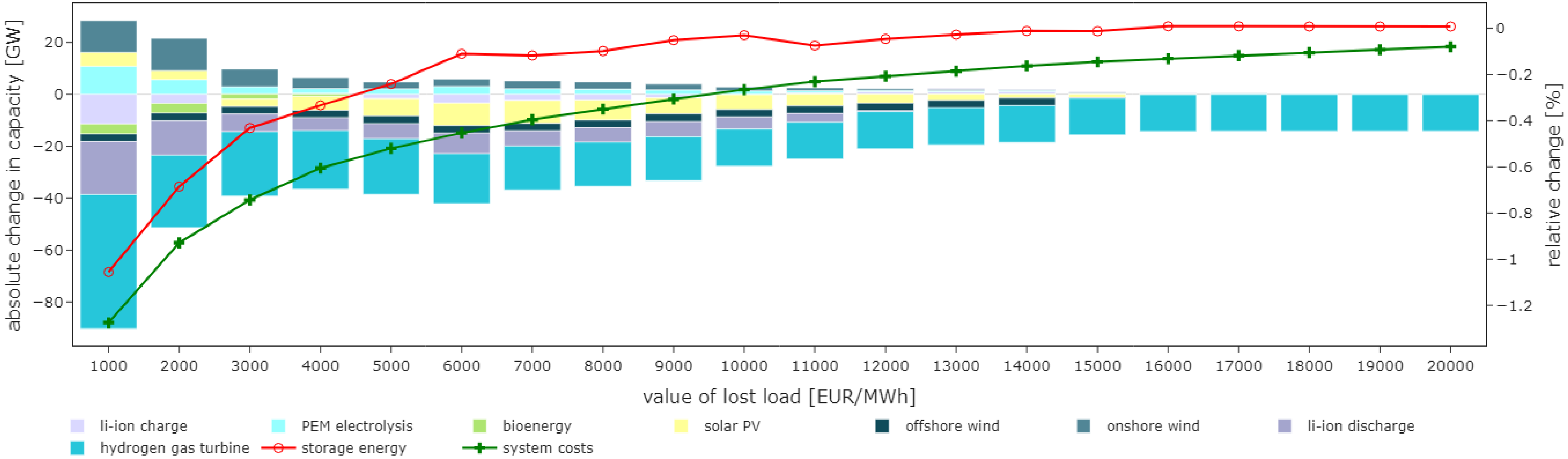
Sensitivity analysis: load shedding

Endogenous load shedding

- Value of lost load (VOLL) as approximation of socio-economic costs: e.g., varies between 7.000 and 17.000 EUR/MWh in Germany
- Note: Not a single cost, but large range for various end energy users

Impact in winter 1996/97 under policy-relevant interconnection (3)

- Lower VOLL displaces long-duration discharging capacity and shorter-duration flexibility such as bioenergy or batteries
- Higher VOLL: effect diminishes
- Long-duration storage energy and system costs hardly affected

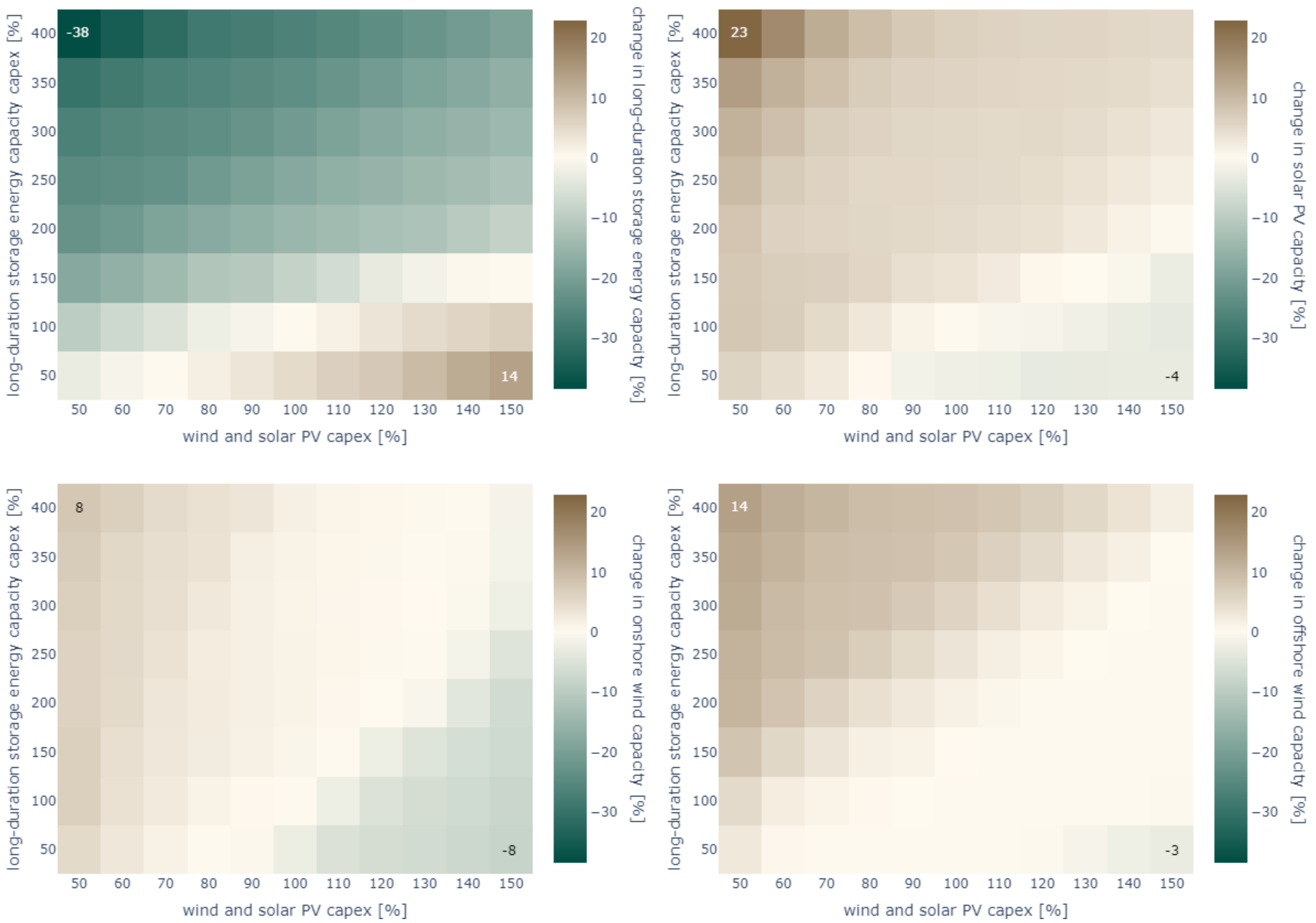


Sensitivity analysis: capex variation for wind, solar PV, and storage energy

Sensitivity for 1996/97 under policy-relevant interconnection (3)

- Massive cost reductions of wind and solar PV → likely to continue with economies of scale
- Hydrogen-based underground storage hardly deployed → larger uncertainty range

- Lower renewable capex favors overbuilding over long-duration storage due to lower residual demand
- Lower storage costs vice versa
- Moderate renewable capex reductions most plausible → storage hardly affected



Conclusion

Known unknowns

- Impact of conventional backup with CCS, load shedding for lower renewable shares (i.e. with nuclear power) → intuition: lower storage need
- Climate sensitivity from climate change: heat demand, wind and solar generation
- Interactions of different hydrogen derivative storage options with long-duration electricity and heat storage
- Perfect foresight assumption impacts long-duration storage operation
- Issue of market power exertion of storage operators as critical elements

Unknown Unknowns

- High impact, low probability events: green, black, gray swan events